

# An Artificial Life Approach to Configuring Architectural Space

Tim Ireland<sup>1</sup>

<sup>1</sup>De Montfort University

<sup>1</sup>tireland@dmu.ac.uk

*This paper presents a method of configuring architectural space that articulates the coupling of an organism with its environment; expressing the spatiality of unfolding engagement in the world. The premise is that space is a consequence of cohesion, effected through constraints and processes of enaction. An Artificial Life model is presented as an analogue of a bottom-up approach to architectural design that takes into account that we as organisms interact with our ever present changing environment and redefine our spatial domain depending on our sensory interaction with said environment.*

**Keywords:** Configuration, Agency, Agent-based modelling, Self-organisation

## INTRODUCTION

Spatial problems are complex. A key constraint in architectural practice is the general reliance on traditional methods to organise architectural layouts, which tend to flatten spatial problems into something quantifiable so they can be managed and planned. Approaching the configuration of space in the standard way raises the question whether any richness is lost? There is often a qualitative disconnect between the articulation of spatiality in the built environment and the spatiality of being. Material properties of objects, and the environment, can be depicted and practical measurements (such as dimension, distance, angle, area, and so on) can be utilised productively to communicate and engineer our mental and physical environment. Spatial problems are inherently situated in the world, which we manage and solve within the confines of geometry. This is the strength of geometry: that it states general laws about geometrical objects and scenarios that we can then apply back to the real world. Simple

operands (i.e., reflection, rotation, subtraction and so forth) can be utilised in solving spatial problems to manipulate parameters without questioning the issue of space. Such mathematical operations provide a cognitive basis for ordering and manipulating the environment, and enable us to manage everyday tasks. More importantly, they allow us to communicate past, current and future spatial scenarios. In a sequence of lectures on 'The Relation of Space and Geometry to Experience' Norbert Wiener claimed that "geometry is the science of a 'form' into which we cast our spatial experiences" (Weiner 1976, p95). Space, he argues, is experiential and that geometry is an abstraction of that experience, being a set of rules by which experience may be replicated.

The spatiality of an organism is an effect of its distributed cognition. The concept introduced by Hutchins (1995) is understood as "the ability of an organism to interact with its environment for the purpose of satisfying its physiological (internal and external) and social needs in order to survive and sus-

tain itself" (Cardenas-Garcia 2013). The capacity of an organism to affect its environment is a result of its mobility and the effect of the environment on the organism (relative to its objective and subjective needs), instigating the organism to act in some particular way. On the basis that design is a constructive activity (Glanville 2006) a distributed cognition approach to design is proposed, whereby an artificial archetypal organism is utilised for the purpose of configuring architectural arrangements. A novel approach to arranging room layouts is presented; taking a behavioural approach that builds on aspects of spatial character and adopts distributed cognition as a driver to generate layouts. The behaviour of natural phenomena is leveraged, such that their activities and goal seeking behaviour is bent towards designing. Looking to distributed (swarm) systems the collective (social) behaviour of natural phenomena is utilised to capitalise on their constructive (i.e. nest building) and configurational (i.e. food foraging and agglomeration of slime moulds) activities. Artificial organisms are used to represent spatial regions, which self-organise according to association parameters. The resulting configurations are akin to bubble diagrams and may thus serve as a basis from which to develop actual architectural arrangements.

## CONFIGURING ARCHITECTURAL LAYOUTS

Planning is the usual way of systematically working through the arrangement of activities in a building, and for all intents and purposes is the process through which an understanding of the building program is determined. Working out the organisation of a building is one of the most important and taxing aspects of the design process concerned with the physical arrangement of objects and areas to fulfil the requirements of the diverse human activities pertinent to a particular building scenario. The success of the plan is in abstracting such problems into two-dimensions to define a plane to render them manageable, so that the numerous intertwined components may be arranged. Experience is an asset in planning, but may be counter-productive as solu-

tions may remain hidden on the basis of 'what one knows', or 'what has been done before'. Architects often fall back on previous plans (as a template) for inspiration, enabling one to judge and construct solutions by interlacing the template with design criteria of a particular scenario. The problem of organising plan layouts is combinatorially hard and has received much attention in the fields of architecture and engineering, particularly since the computer came to be utilised as a tool for analysis and design.

The field of automatic plan generation is composed of two distinct approaches. (1) optimisation, which automates planning to present a single 'best solution' according to specified objective function(s), (aligned to the objective of shortest path in wiring diagrams) and (2) enumeration, which presents possibilities to enable exploration of alternatives. The latter presents a 'world of alternatives' to open up the designer to possibilities (Steadman 1970; Mitchell, Steadman and Liggett 1977; Flemming 1986, 1990). Another distinction is between methods that are interactive and engage the user. The LOOS model by Ulrich Flemming (1986, 1990) generated 'loosely packed' arrangements of rectangles. This diagrammatic resolution maintained a level of ambiguity generating partial solutions; seen as a step in the process towards resolving arrangements, but not to produce a final layout. Flemming focused on the intermediate stage of space allocation to generate arrangements in which rectangles describing crucial spatial relations between the primary elements are allocated. Circulation spaces were not specified at the outset, and so the process generated arrangements containing "gaps or holes that are used later to allocate auxiliary spaces or that are added to previously allocated spaces once the shape of the circulation area has been determined" (Flemming 1986, p192).

Methods to automate the generation of planned layouts diminished in the mid 80's, by those who pioneered them, because architects in practice were turned off by the approach and due to three basic logical difficulties:

1. The strengths of association between spaces were defined in practice by surveying patterns of movement in existing buildings of the same type - which may of course be the result of the plans considered. Fundamentally the spatial relations used to generate a plan were based on existing plans so in essence what was generated was a replication, or alternatives of the same spatial arrangement.
2. Circulation tended to be privileged above all other generic functions. This is certainly true of the first group, whereby the resulting layouts became optimised on this basis, which tended to produce centralised layouts, tightly clustered around the most strongly connected space(s).
3. Circulation spaces were specified at the outset, which is the opposite to what tends to occur in practice, where circulation is often a consequence of the room arrangement. Note: There is an issue of scale here. Specifying circulation in a small house is not unreasonable; as only a central circulation space, such as a hall from which all spaces are accessible is required. Else, in the case of two levels a stair with landing on the next level is also required, from where, again all other spaces are accessible.

### ***Recent and current work in the field of automatic plan generation:***

There has been a resurgence of interest in the automatic planning of layouts using a variety of computing techniques: such as shape grammars (Duarte 2003); evolutionary methods (Rosenman 1997; Rosenman and Gero 1999; Jo and Gero 1998; Elezkurtaj and Franck 2002, 1999); physically based modelling (Arvin and House 1999, 2002, Arvin 2004); agents (Ophir 2009; Ireland 2010); three-dimensional planning and conceptual form generation (Hsu and Krawczyk 2003, 2004; Derix 2010; Ireland and Derix 2003). These efforts have occurred both in an academic and commercial context. The latter has

occurred as a result of architectural practice coming to terms with computation and large architectural practices employing computational design/research teams to operate at the edge of practice and academia. This re-interest seems to have occurred, not least because architectural planning is a complex problem and a key aspect of the design process, but because no model has yet met the requirements of practice, and new computational techniques provide alternative approaches towards achieving this.

One focus of attention in modelling spatial arrangement that is of particular interest to this work is (what may be called) automatic space adjacency analysis, because it is focused on the pre-planning stage aimed at generating partial solutions. Architects archetypally use space adjacency analysis (such as bubble diagrams) as a way of considering the layout of functions in a floor plan, to explore relationships among the sizes, adjacencies and approximate shapes of spaces needed for various activities (White 1986, Do and Gross 2001). A recent example of automatic space adjacency analysis is the tool developed by the computational design research team at Aedas (UK) Ltd. for the design of the Abu Dhabi Education Council's new headquarters (Abrahams 2011). Their model used an attract-and-repel algorithm to organise the spatial adjacencies stipulated in the building brief. (See also Arvin 2004).

Planning is an inherently top-down activity, which tends to focus on adjacency and connectivity. There is an inclination to locate areas according to functional requirements with an emphasis on connectivity according to a scale of importance. Those which have a high correlation are placed adjacent to one another, or as close as possible, while others are located at decreasing distances according to the importance of their connectivity. "An adjacency objective is a topological objective that influences the distance between two spaces. For example, two spaces that have a large amount of traffic between them may be specified with an immediate adjacency" (Arvin and House 2002). Spatial relations, naturally, constitute much greater variance than the typical fo-

cus allows for. Whilst it is clear that topology is a fundamental aspect of reasoning about space qualitatively, it only accounts for particular distinctions. In the context of synthesising spatial relations we need to be able to examine a relation and account for conditions of both connection and parthood. Taking a mereotopological approach allows a more encompassing approach to establishing spatial relations between constituents: (see Casati and Varzi 1999).

The approach of Hsu and Krawczyk (2003 and 2004) is of particular interest to this study. They describe rooms as having characters, making the analogy between configurations of people and the task of configuring rooms. "If we consider a space is a person, and a group of people who gather according to similar requirements, we can then assume every space has its own 'space character', either in a very abstract or practical sense, or both" (Hsu and Krawczyk 2003). The relations between rooms, and to a site, are thus transformed into 'spatial characters' arranged accordingly in a space-planning program. Hsu and Krawczyk define space adjacency as behavioural, applying certain traits of human activity to the parameters of a space. For example, a room taking advantage of, or requiring, a view is perceived 'a watcher', requiring a location against the building perimeter to take advantage of a particular attraction. The approach taken in this study is similar, but opens up the potential of spatial arrangements in a manner reflecting pattern formation in natural systems; which are not specifically constrained by topological relations. The model thus reflects a naturalised conception of space (Ireland 2015) and presents a bottom-up approach to spatial configuration.

## AN ARTIFICIAL LIFE APPROACH

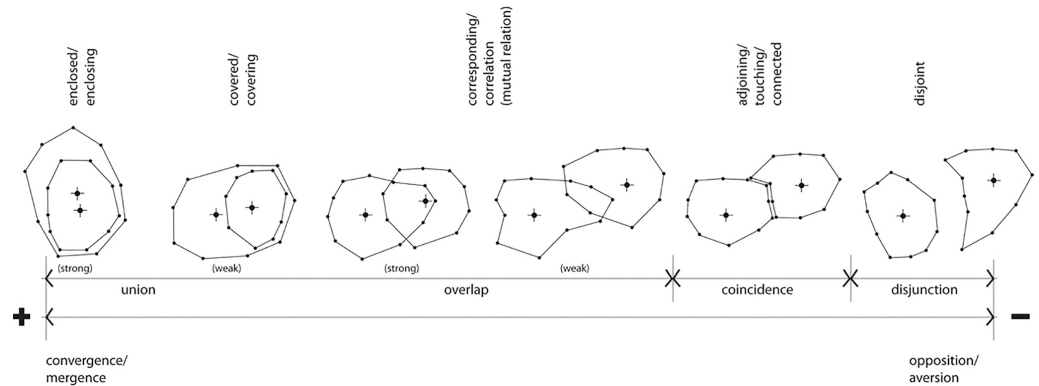
Various organisms have developed the capacity to modify their environment in such a way that they construct artefacts. These structures embody the subject's intelligence, and whilst human-beings may be understood to create artefacts 'par excellence' their constructs are ingrained by patterns of inhabitation, which (from an evolutionary perspective) may

be extended downwards. Scrutinising built structures enables us to consider 'lived-space' retrospectively as a system of social relations and to thereby extrapolate particular rules, or patterns, of inhabitation. Bill Hillier and Julienne Hanson (1984) transported themselves within the plans of built forms to review their organisation, and illustrated how the configuration of space alters when specified from the discrete perspective of each room location. Identifying architectural-space to be heterogeneous they illustrate buildings to be social-systems determined by the dynamics of habitation. Perceived in this way architectural-space exhibits structure and constitutes organisation, becoming a sort of medium, established through a system of relations.

The model presented draws on the theory of organism-environment relations by Barry Smith and Achille Varzi (2002). They define elemental forms of interaction between organism's, to reflect contrasting sorts of interaction and how these affect the niche of an organism: the niche of an organism equating to its territory. In short what is proposed is *a general hypothesis for creating causally relevant spatial regions that generate spatial formation in a cell-like manner*; on the basis that the cell is the primal organism. A cell may be defined, in abstract, as a niche with the ability to distinguish self from non-self that acts according to differences in the environment, which mean something and that this meaning has spatial consequences according to the significance of the difference relative to the state of the perceiving 'self'. The basic component of the model is an actant (a term borrowed from Bruno Latour (1996) to refer to an autonomous entity-in-its-environment), which is an artificial cell-like organism that represents a region of space. Actants coalesce with one another according to their relations to form an aggregation; which is deemed to represent a pattern of habitation pertinent to the spatial-regions represented.

Smith and Varzi identify four elemental forms of interaction: (a) coupling, (b) nonchalance, (c) encounter (which may be a collision or impingement) and (d) contrast (which may be conflict or incompat-

Figure 1  
Scale of  
consolidation



ibility). Whilst (b) expresses commonality the other exchanges lead to deformations of the organisms niche: the latter (c and d) in terms of negative deformation and (a) to positive deformation. These forms of interaction are extended for this study to define relation potentials, establishing forms of association between one actant and another. These associational parameters distinguish the spatial-property of a relation as a scale, not of dimension, but as a gradient or degree of consolidation. The relation-potentials between one actant and another are thus sub-sumptive. (See Figure 1).

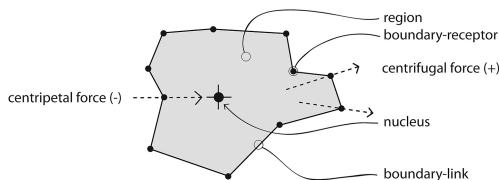
### ***The basic component of the computer model***

An actant represents a region of space, depicted by a boundary composed of 'boundary-nodes' that are linked, and describe the actants form. The boundary is a mutable entity, because the boundary-nodes have the capacity to affect and be affected. Their configuration therefore affects the actants conformation. The boundary consisting of nodes, which act as the actants receptors, and effectors, are affected by differences detected in the environment. These nodes (referred to as boundary-receptors) are agents which move collectively while emitting and responding to differences. These differences are created by the actants emitting pheromone, which acts as a signal

to other actants because each actants pheromone is unique. As a difference, the pheromone can affect the actant by constituting a centrifugal or centripetal force on the nodes, thereby affecting the actants current location relative to the difference detected. Fundamentally an actant constitutes an abstract swarm, with the capacity to distinguish self from non-self. The pheromone an actant emits acts as a unique signal, identifying itself to other actants. Each actant thus has an identity, which its components share and to which other actants refer. A difference may therefore be 'observed' by the actant, through its boundary-receptors as something which is not an aspect of its identity. The actant will thus respond to the difference detected by positioning itself according to the significance: i.e., the association with the other actant detected. Consequently, the actants configure themselves according to those actants they have an association (or dissociation) with by responding to their signals. Configuration arises in the model as a result of boundary conformation, determined by the way the boundary-receptors respond to differences detected. (See figure 2).

The form of association and behaviour of an actant is determined by its capacity to sense, and distinguish differences present in its environment. The differences thereby have meaning for an actant, acting as a signal, according to the significance of the

difference detected. The actants thereby respond to a difference according to the association. If the association is positive an actant will move towards the difference (i.e. towards the source of production and thereby moving in the direction of an associate). Otherwise the actant will back off, moving away from the source in a direction elsewhere from its dissociate. Figure 3 shows actants responding positively to differences they detect in their environment in various circumstances. In the first instance to a point source, secondly to a trail and thirdly to another actants signal.



The actants are building blocks to generate patterns of configuration autonomously, whose behaviour may be steered and manipulated to suit particular objectives, by affecting their associations. An actant moves through the collective actions of its boundary-nodes, which move relative to their distance from the nucleus and nearest boundary-node neighbour. The former is a simple attract-repel mechanism: if too close to the nucleus move away and if too far away it move towards it. The latter a repel mechanism from the closest boundary-node of the same niche. This results in a wandering-like behaviour in which the collective moves in a unified manner, reminiscent of the movement of amoebae. An actant wanders in this way for a period until, if no other actants are sensed, one of its boundary-receptors is selected to become a 'hunter'. Having been selected the hunting boundary-receptor will move away from the nucleus, extending its search space to check for associate boundary-receptors beyond the niche's immediate vicinity. If another boundary-receptor is perceived the hunter will position itself according to the relation between the two activity-niches: see right-hand image of figure 3. Otherwise the hunter

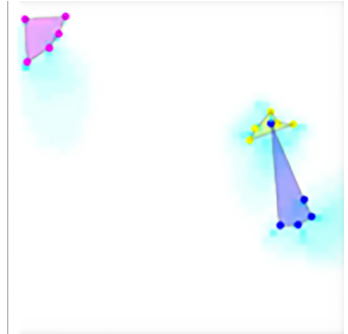
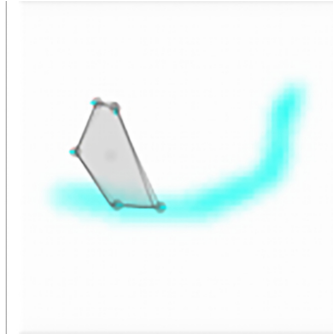
switches state back to boundary-receptor and settles back. This hunting action is analogous to the cellular extensions of amoeboid type cells used in moving and feeding. The propulsion of the extension can affect the course of the niche's wandering. If no associate is sensed after another period of wandering the hunting behaviour is repeated. The autonomy and sensorial capacity of an actant means that its form is changeable. It is a mutable figure affected by the conditions in which it is situated, which is diachronic: being affected by motion, the actants composition and individual relations.

### ***Pheromone Contingency***

The form of association and behaviour of an actant is determined by its capacity to sense, and distinguish differences present in its environment. An actant is equipped with the capacity to 'smell', which is enabled through the capacity to distinguish contrasting forms and levels of pheromone. The pheromone thereby has meaning for the actant, acting as a signal. The actants thereby respond to the pheromone according to the association, following pheromone 'uphill' (towards the source of production and thereby moving in the direction of an associate) if there is a positive relation and 'downhill' (moving away from the source in a direction elsewhere from a dissociate) if there is a negative relation. This mechanism defines attract-repel behaviour reminiscent of predator-prey relations. With this in mind the emission of pheromone is determined by the state of the boundary-nodes, such that they only emit pheromone when open to being found; imitating slime mould behaviour whereby the individual spores only emit pheromone when they are in a state of hunger; causing them to aggregate. Likewise, a boundary-node only emits pheromone when it is not evading and seeking, thereby discouraging aggregation with dissociates. Since pheromone acts as a signal it would be perverse to remain signalling to a dissociate whilst evading, and to inform an associate (to whom one is a dissociate) of one's presence, thereby aiding evasion. To ensure an actant which is

Figure 2  
An actant: the basic component of the model

Figure 3  
Stills from the  
computer model  
showing an  
activity-niche  
responding to  
pheromone. (Left)  
to a pheromone  
source, (centre)  
following a  
pheromone trail,  
and (right)  
engaging with an  
associate  
activity-niche.



dissociated to that which perceives it an associate is not disadvantaged its sense of pheromone is more acute: creating asymmetry in the actants capacity to sense pheromone. Referring to the hunter/prey condition we can see that an actant that is prey (it is dissociate to another for which it is associate) wants to evade. It therefore needs to be alert to any encroachment from dissociates, and so the threshold for sensing dissociate pheromone is therefore lower than for sensing an associate. Alternatively the hunter wants to be, as it were, 'quick off the mark'. Successful evasion/invasion is dependent upon the situation determined by the trajectory of actants and the presence (history) of pheromone. This means that the hunter/prey condition is opportunistic, because whether the prey evades or the hunter attains is a matter of directionality. The situation tends to be better for the 'hunter' if the approach is from the 'front'; which equates to the direction of movement because the pheromone, as a deposit, tends to form a trail.

### A DISTRIBUTED COGNITION PERSPECTIVE OF CONFIGURATION

The model presents a process whereby configuration is the result of the multiplicity of interactions between the actants with their own timing, spacing, goals, means and ends. At a basic level the attract-repel mechanism (described above analogically as predator-prey) relates to contrasting social relations,

defining conditions analogous to situations between areas which have conflicting social properties, such as one being public the other private or environmental properties where the effect of one is noise whilst the requirement of another is quiet. In such cases one actant will seek to evade the other. However, the activities people perform, and the associations between them are not necessarily fixed. Our activities may be habitual but they fluctuate depending on physiological and social needs. Whilst the model as it stands does not account for such 'fluctuating' conditions the configurations generated are the result of the actants individual timing, spacing and goals. (See figure 4). The result of this is that, whilst the resulting configuration satisfies the individual actants associates the arising configuration is different each time, because history is a significant aspect of the model. Also, the actants 'behaviour' is tensive, because an actant that has settled (having satisfied its associations) may become unsettled by other actants actions. This can cause the overall configuration to unravel, because if a settled actants associate is unsettled it is then caused to move; spoiling the settled actants state of harmony, causing them to re-seek their state of cohesion. This is good, because the final configuration rests on the harmony of all actants realising their individual relation potentials. Configuration in the model is aggregative.

The individual actants conformation and thus the concluding configuration are determined by the

behaviour of the population. Looking back at the middle image of figure 3, we see an actant responding to a pheromone trail. The actant is in the process of adapting to its environment according to the differences it 'perceives'. Relating this to how people respond to their changing environment, and how our activities change or the way we alter our surroundings to reflect (for example) a changing climate we can see how the actants transformation reflects this: changing from one stable state to another. Before detecting the pheromone it is in one state, but having detected 'a difference' it responds to that difference (and follows the pheromone trail) and settles into another state once that difference has been 'accommodated': i.e. it reconfigures its boundary conformation to changing conditions. The model reflects how an organism moves from a stable spatial domain, representing a given understanding of

said spatial domain at a specific time, to another stable but different spatial domain due to the organism sensing changes in its environment and adapting to such changes. For example, in much the same way that the internal state of an organism may change according to external perturbations, an inhabitant sensing a changing climate may alter the configuration of his or her living quarters to accommodate or embrace changing external conditions: thereby satisfying physiological needs. The model is an analog of a bottom-up approach to architectural design that takes into account that we as organisms interact with our ever present changing environment and redefine our spatial domain depending on our sensory interaction with said environment. The changes affecting our sensory interaction are not only physiological, but are social too. For example, whilst we might engage in seasonal changes of our living quar-

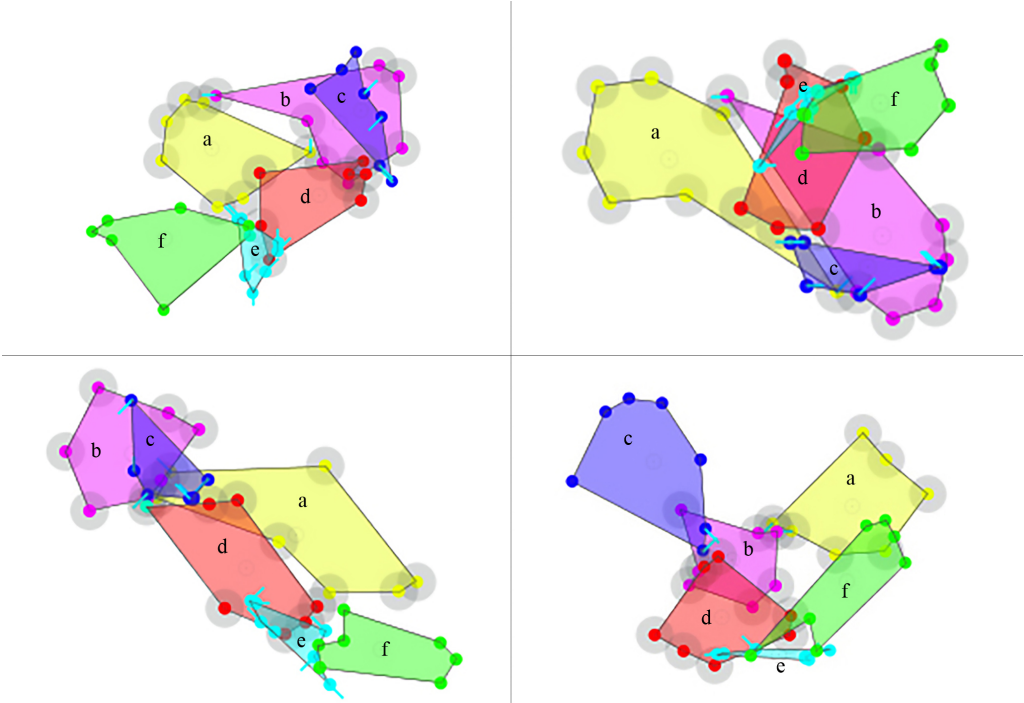


Figure 4  
Actants settled in  
different  
configurations  
according to their  
associations



ters due to perceiving changes in our spatial domain consequent to external conditions, changes may also occur as a result of social or life events.

The relation between one actant and another is causal, the significance of which is contingent on the conditions particular to each actant. Each actant deposits a unique pheromone, thereby identifying itself to other actants. The actants thus configure themselves according to those actants they have an association (or dissociation) with by responding to their pheromone. The point being that the 'form' of the pheromone relates to what meaning it holds for the individual actants. The pheromone may represent many other factors other than whether one activity relates to another: such as daylight, noise, a view, and so forth because the pheromone simply represents a difference; which (if the pheromone represents something of significance to an actant) is something which either attracts or repels an actant.

## CONCLUSION

What has been presented is a conceptual materialisation of spatial configuration, in a way reflecting the behaviour of spatial formation found in natural systems: such as slime mould aggregation. By taking such cases into account, the model here presented can serve as a starting point for an artificial life approach to generating architectural layouts. The model illustrates a novel user-centric method, taking a behavioural approach that accounts for an organisms sensorial engagement with its environment, and demonstrates a general hypothesis for creating causally relevant spatial regions that generate spatial formation in a cell-like manner.

As it stands the model does not generate results an architect may utilise. The computer model needs further development and, as is, stands as a rhetorical device for the theoretical perspective and approach argued for. There are two significant issues, which the results (figure 4) illustrate, that require attention. (1) the actants associations are purely subjective, which leads to (2) the models practical implementation. The actants should have objective, as well

as subjective, parameters to satisfy, such as maintaining a min-max area. Of the relation-potentials presented (figure 1) only weak overlap, coincidence and disjunction are accounted for. The computer model demonstrates a scale-of convergence but extending it to allow for greater variance would enrich its output. Development of the model lies, initially, with resolving these two key aspects. Further development lies in extending the forms of pheromone, so as to incorporate site contingent factors such as views, access and environmental constraints, so that the actants may respond to greater variances. Further enhancement of the actants sensorial capacity would benefit the ability of actants to engage with differences present in their environment. A question then stands as to whether the computer model is to be taken as a conceptual diagramming tool (along the lines of Flemmings (1990) LOOS programme) or is developed for more practical consideration. The author suggests the former most beneficial, so that the model stands as an explorative aid rather than a tool for solving planning problems. Developing the model into 3dimensions would extend it beyond the standard 2dimensional perspective adopted in planning and serve to articulate Smith and Varzi's (2002) general theory of causally relevant spatial volumes.

## THANKS

This paper stems from my PhD thesis (completed 2013). I thank my supervisors Philip Steadman and Paul Coates for their input, encouragement and support, and the EPSRC for funding. Thanks also to Jaime Cardenas-Garcia for his on going discussion and input on distributed cognition and relevance to the computer model.

## REFERENCES

- Abrahams, T 2011, 'Office Design by Tetris', *WIRED (UK)*, 9th December 2011
- Arvin, S.A. 2004, *Physically Based Mechanical Metaphors in Architectural Space Planning*, Ph.D. Thesis, Texas A&M University
- Arvin, S.A. and House, D.H. 2002, 'Modelling Architectural Design Objectives in Physically Based Space

- Planning', *Automation in Construction*, 11(2), p. 213–225
- Arvin, S.A. and House, D.H. Modeling Architectural Design Objectives in Physically Based Space Planning 'Modeling Architectural Design Objectives in Physically Based Space Planning', *Proceedings of ACADIA 1999*, Salt Lake City, Utah, pp. 212–225
- Bateson, G 2000, 'Form, Substance and Difference', in -, - (eds) 2000, *Steps to an Ecology of Mind*, The University of Chicago Press, Chicago, pp. 454–471
- Cardenas-Garcia, J.F. 2013, 'Distributed Cognition: An Ectoderm-Centric Perspective', *Biosemiotics*, 6(3), pp. 337–350
- Casati, R and Varzi, A.C. 1999, *Parts and Places: The Structures of Spatial Representation*, A Bradford Book, The MIT Press, Cambridge, Mass
- Derix, C. 2010 'Mediating Spatial Phenomena through Computational Heuristics', *Proceedings of ACADIA 2010*, New York, pp. 61–66
- Do, E.Y. and Gross, M.D. 2001, 'Thinking with Diagrams in Architectural Design', *Artificial Intelligence Review*, 15, pp. 135–149
- Duarte, J. P. 2003 'A Discursive Grammar for Customizing Mass Housing: The case of Siza's houses at Malagueira', *Proceedings of eCAADe 2003*, Graz, pp. 665–674
- Elezkurtaj, T. and Franck, G. 1999 'Genetic Algorithms in Support of Creative Architectural Design', *Proceedings of eCAADe 1999*, Liverpool, pp. 645–651
- Elezkurtaj, T. and Franck, G. 2002, 'Algorithmic Support of Creative Architectural Design', *Umbau*, 19, pp. 129–137
- Flemming, U. 1986, 'On the Representation and Generation of Loosely Packed Arrangements of Rectangles', *Environment and Planning B: Planning and design*, 13(2), pp. 189–205
- Flemming, U. 1990, 'Knowledge Representation and Acquisition in the LOOS System', *Building and environment*, 25(3), pp. 209–219
- Glanville, R. 2006, 'Construction and Design', *Constructivist Foundations*, 1(3), p. 103–110
- Hillier, B. and Hanson, J. 1984, *The Social Logic of Space*, Cambridge University Press
- Hsu, Y. and Krawczyk, R.J. 2003 'New Generation of Computer Aided Design In Space Planning Methods - a Survey and A Proposal', *Proceedings of CAADRIA 2003*, Bangkok, pp. 101–116
- Hsu, Y. and Krawczyk, R.J. 2004 'Space Adjacency Behaviour in Space Planning', *Proceedings of CAADRIA 2004*, Seoul
- Hutchins, E. 1995, *Cognition in the wild*, MIT Press, Cambridge, Mass.
- Ireland, T. 2010 'Stigmergic Planning', *Proceedings of ACADIA 2010*, New York, pp. 183–189
- Ireland, T. and Derix, C. 2003 'The Poly-dimensionality of Living: An Experiment in the Application of 3-Dimensional Self-Organising Maps to Evolve Form', *Proceedings of eCAADe 2003*, Graz, pp. 449–455
- Ireland, T. 2015, 'Naturalising Space', in Perrin, C. and Mlecek, M. (eds) 2015, *Perception in Architecture: HERE and Now*, Cambridge Scholars Publishing, pp. 38–46
- Jo, J.H. and Gero, J.S. 1998, 'Space Layout Planning Using an Evolutionary Approach', *Artificial Intelligence in Engineering*, 12(3), p. 149–162
- Latour, B. 1996, 'On Actor-Network Theory. A Few Clarifications Plus More than a Few Complications', *Soziale Welt*, 47, pp. 369–381
- Mitchell, W., Steadman, P. and Liggett, R. 1977, 'Synthesis and Optimization of Small Rectangular Floor Plans', *Environment and Planning B: Planning and design*, 4(81–88), p. 1
- Ophir, Y. 2009, 'Collective Intelligence: An Agent-Based Approach to Programmatic Organization in Architecture', *International Journal of Architectural Computing*, 7(3), pp. 479–499
- Rosenman, M.A. 1997, 'The Generation of Form Using an Evolutionary Approach', in Dasgupta, D. and Michalewicz, Z. (eds) 1997, *Evolutionary Algorithms in Engineering Applications*, Springer-Verlag, pp. 69–85
- Rosenman, M.A. and Gero, J.S. 1999, 'Evolving Designs by Generating Useful Complex Gene Structures', in Bentley, P. (eds) 1999, *Evolutionary Design by Computers*, Morgan Kaufmann, San Francisco, pp. 345–364
- Smith, B. and Varzi, A.C. 2002, 'Surrounding Space: The Ontology of Organism-Environment Relations', *Theory in Biosciences*, 121, p. 139–162
- Steadman, P. 1970, 'The Automatic Generation of Minimum-standard House Plans', *Land use and built form studies*, working paper 23 (University of Cambridge Department of Architecture)
- White, E.T. 1986, *Space Adjacency Analysis: Diagramming Information for Architectural Design*, Architecture Media.
- Wiener, N. 1976, 'The Relation of Space and Geometry to Experience', in Masani, P. (eds) 1976, *Collected Works with commentaries. Volume 1*, MIT Press, Cambridge Mass., pp. 87–214